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Todorov

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(54) **ROBOT WITH BELT-DRIVE SYSTEM**

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B66C 23/00	(2006.01)
B25J 18/00	(2006.01)

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USPC **74/490.05**; 74/490.07; 74/490.01; 901/15; 901/21; 414/744.3

(58) **Field of Classification Search**

USPC 74/490, 490.01, 490.02, 490.04, 74/490.05, 490.07; 901/15, 21; 414/744.1–744.6; 187/222, 224; 474/61, 62

See application file for complete search history.

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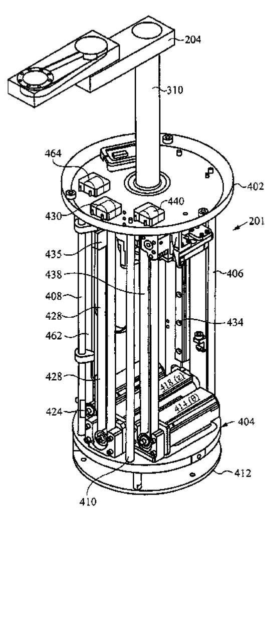
(57) **ABSTRACT**

A substrate handling robot having a robot body and a robot arm with an end effector is configured to exhibit angular (θ), radial (R) and Z motion. A pair of coaxial shafts link the robot arm to respective motors dedicated to angular (θ) and radial (R) motions. The motors are stationarily mounted with respect to the robot body. The shafts are rotatably supported by a floating platform which is motivated in the Z direction by a third motor also stationarily mounted with respect to the robot body. The third motor is coupled to the platform by a Z motion linkage. The first and second motors are coupled to the coaxial shafts by angular and radial motion linkages each of which includes primary and secondary timing belts whose relative motions are synchronized with the Z motion linkage to achieve controllable independent angular (θ), radial (R) and Z motions in a simple, light-weight package.

15 Claims, 14 Drawing Sheets



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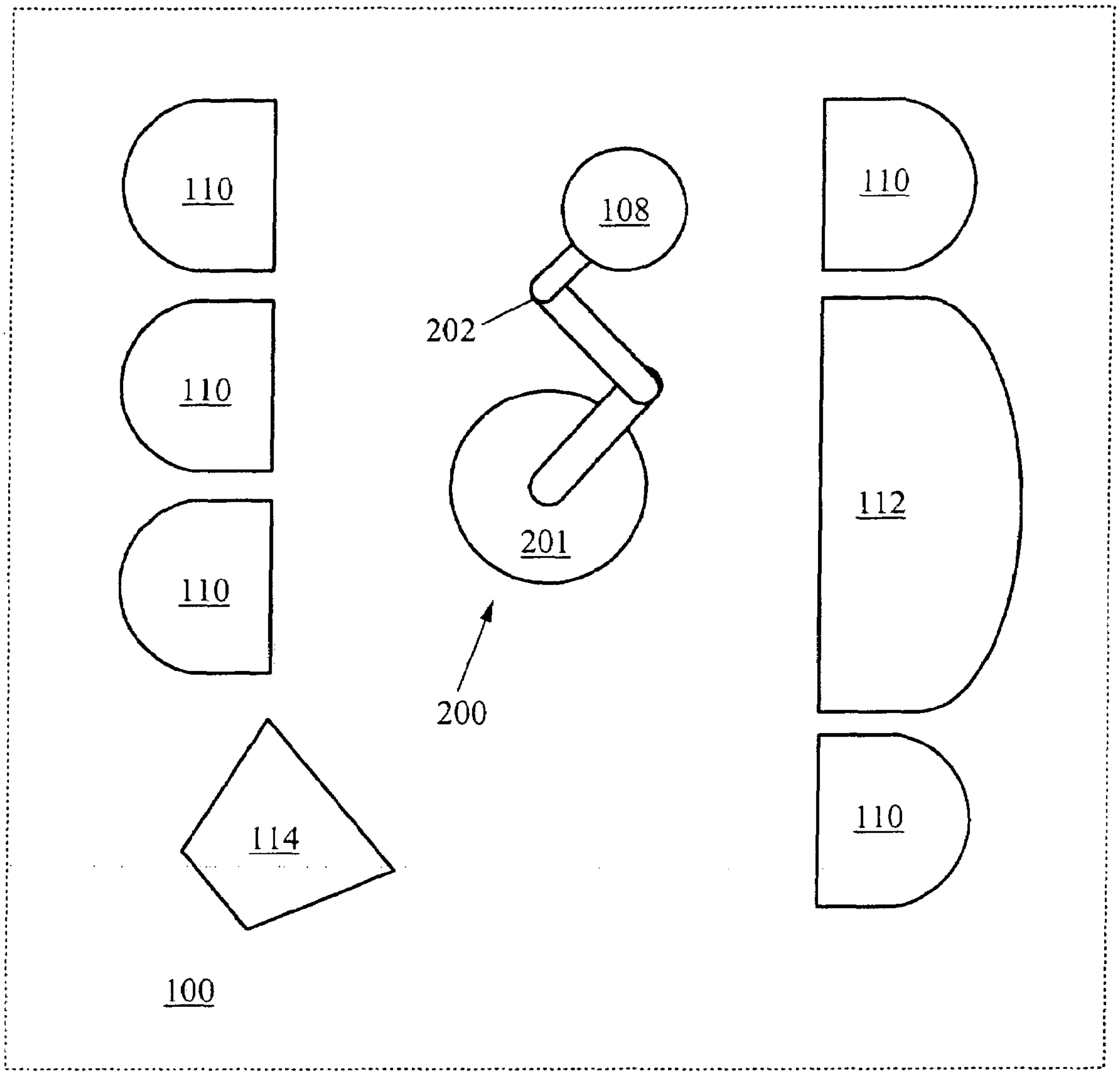


Fig. 1

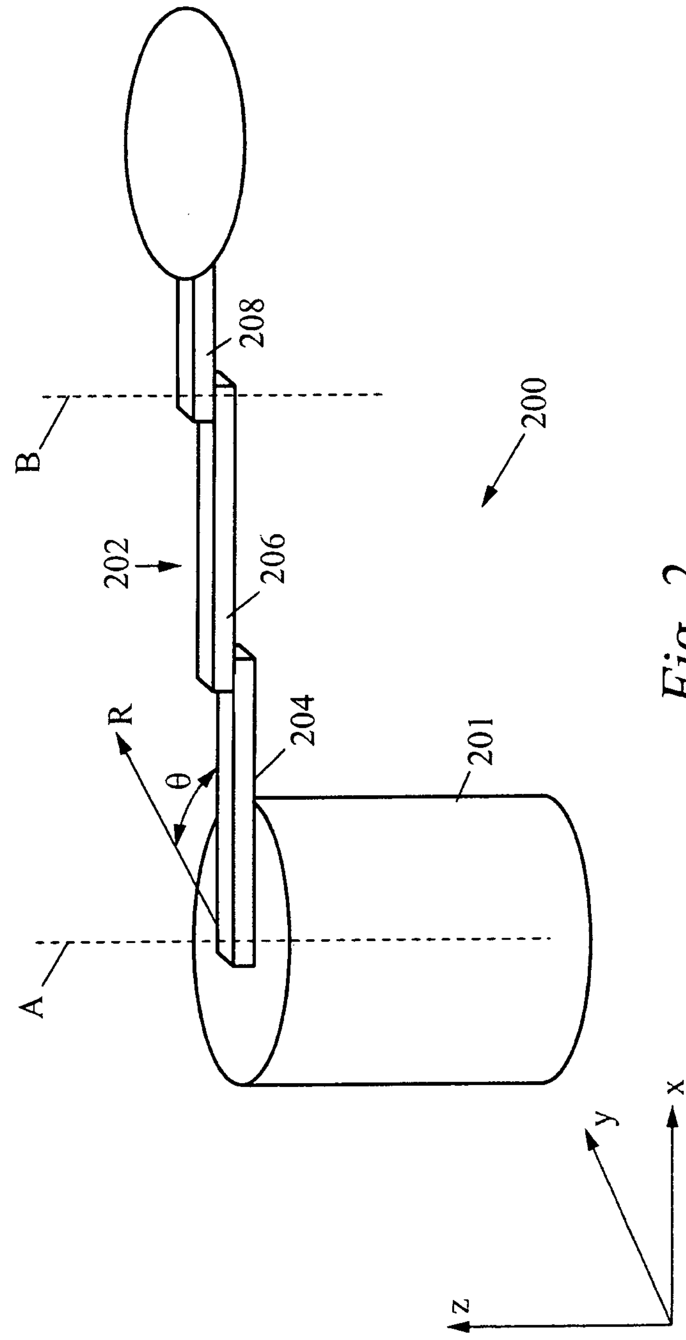


Fig. 2

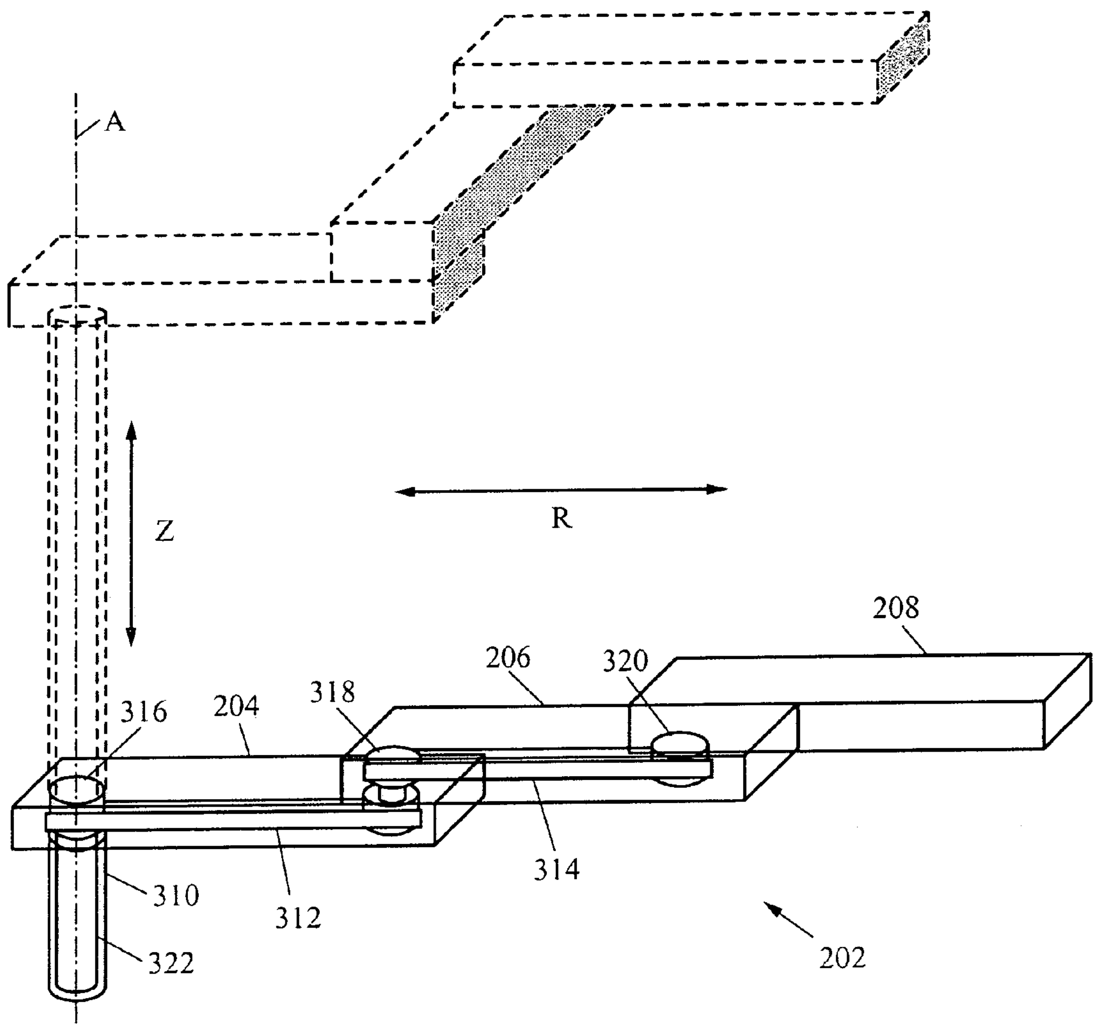


Fig. 3

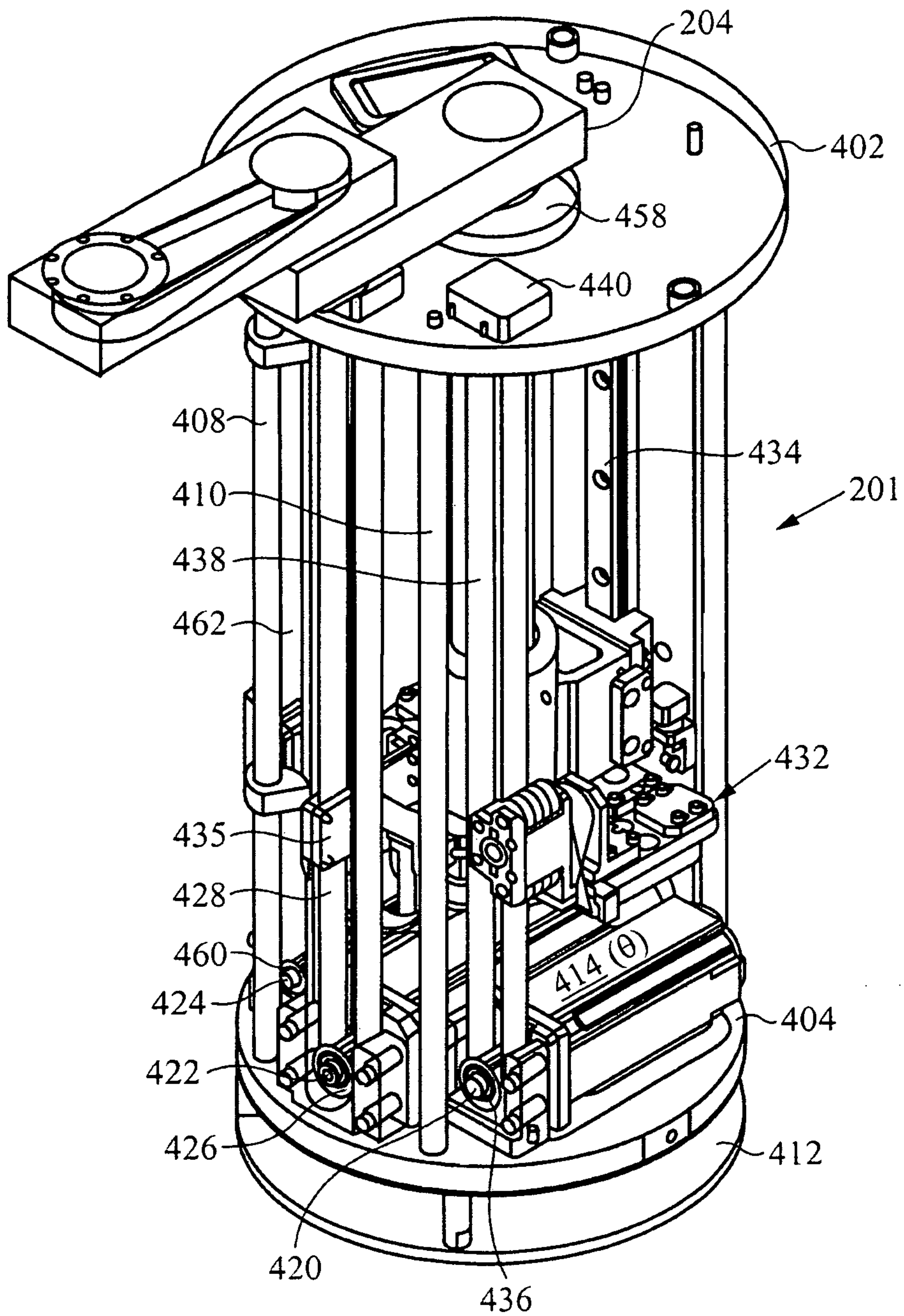

204
402
458
440
408
434
201
410
438
462
432
435
428
460
414 (θ)
424
404
422
426
412
420
436

Fig. 4

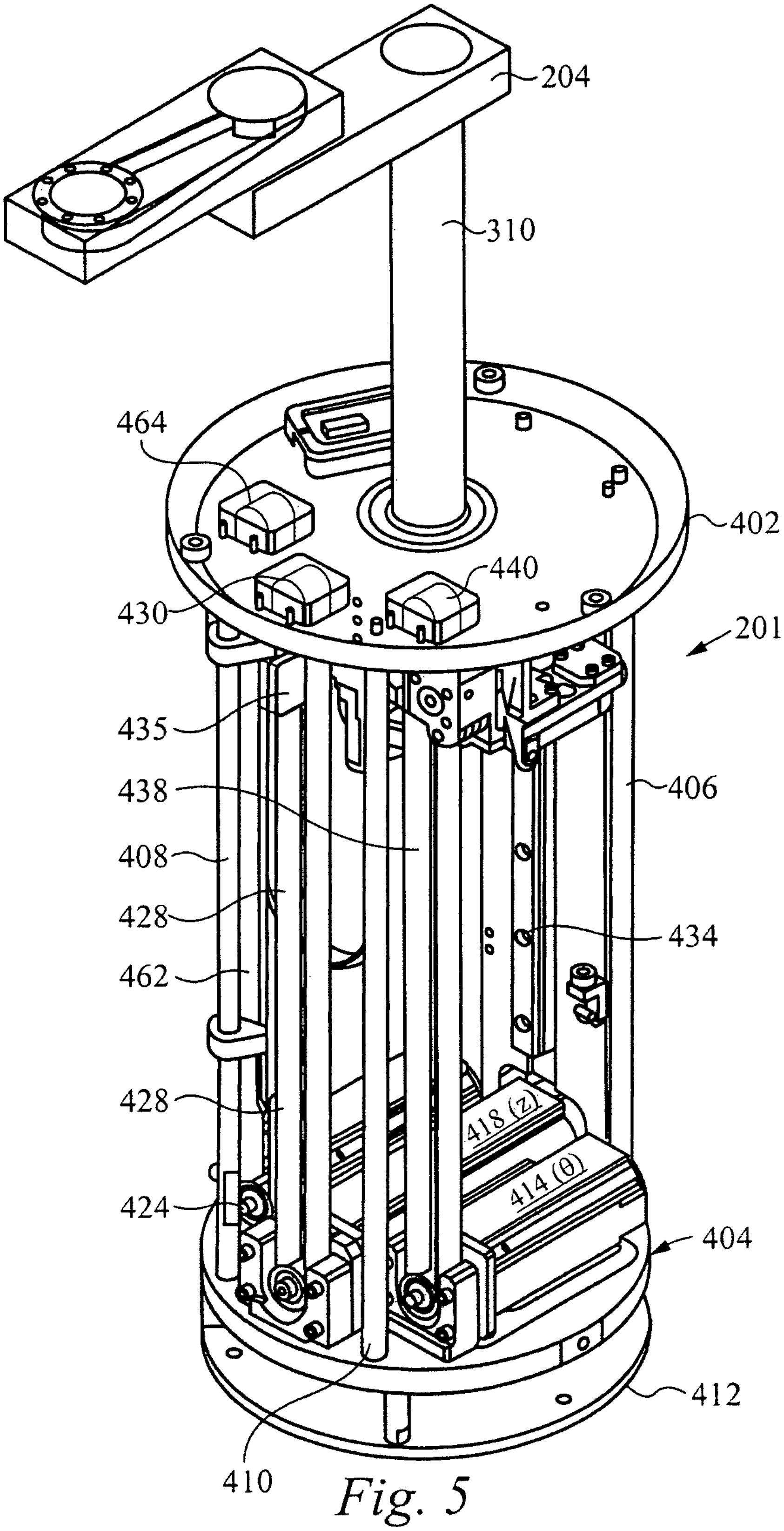
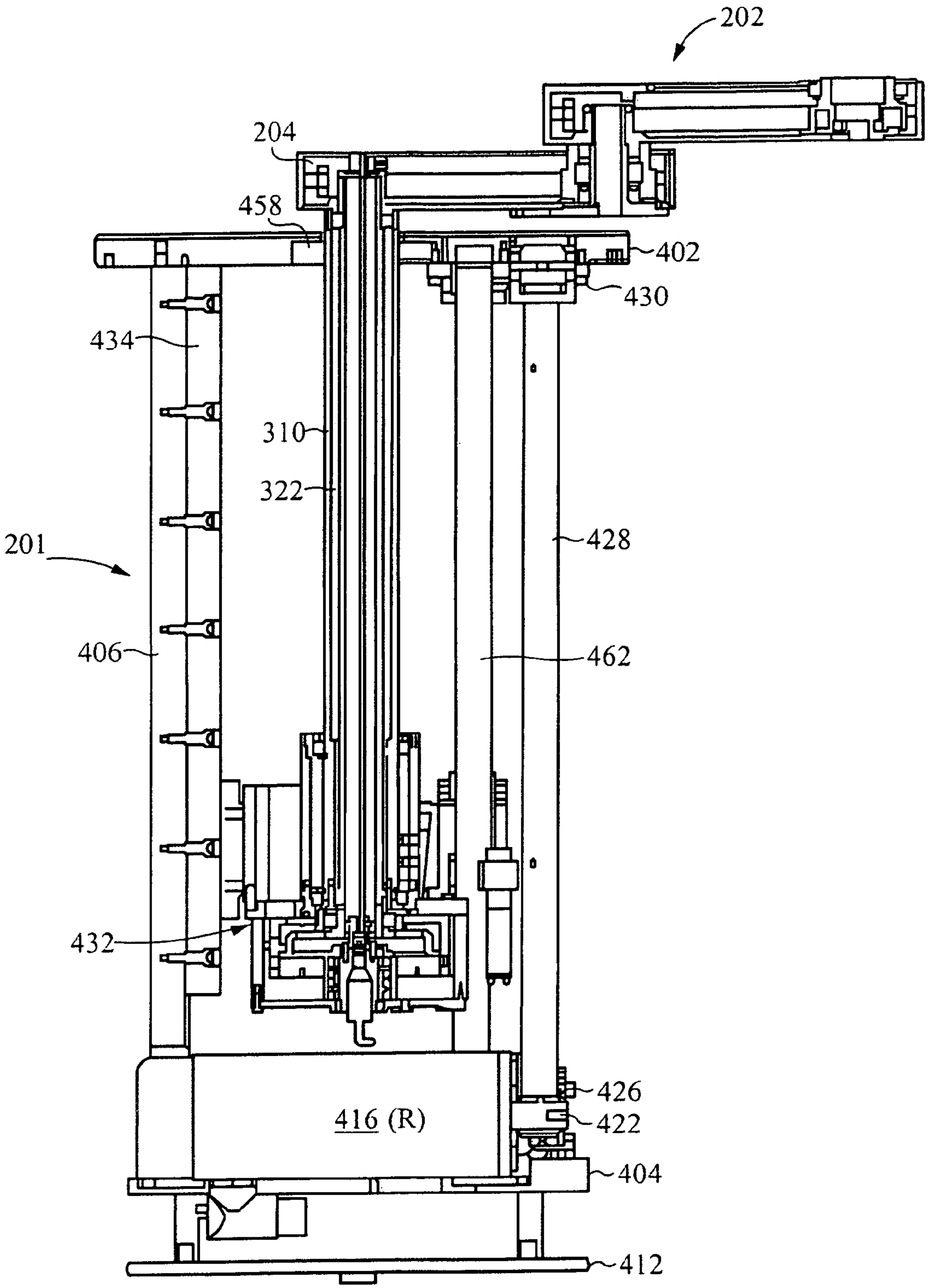

204
310
464
402
440
430
201
435
406
438
408
428
434
462
428
418 (z)
414 (θ)
424
404
412
410

Fig. 5



202
204
458
402
430
434
310
322
201
428
406
462
432
426
416 (R)
422
404
412

Fig. 6

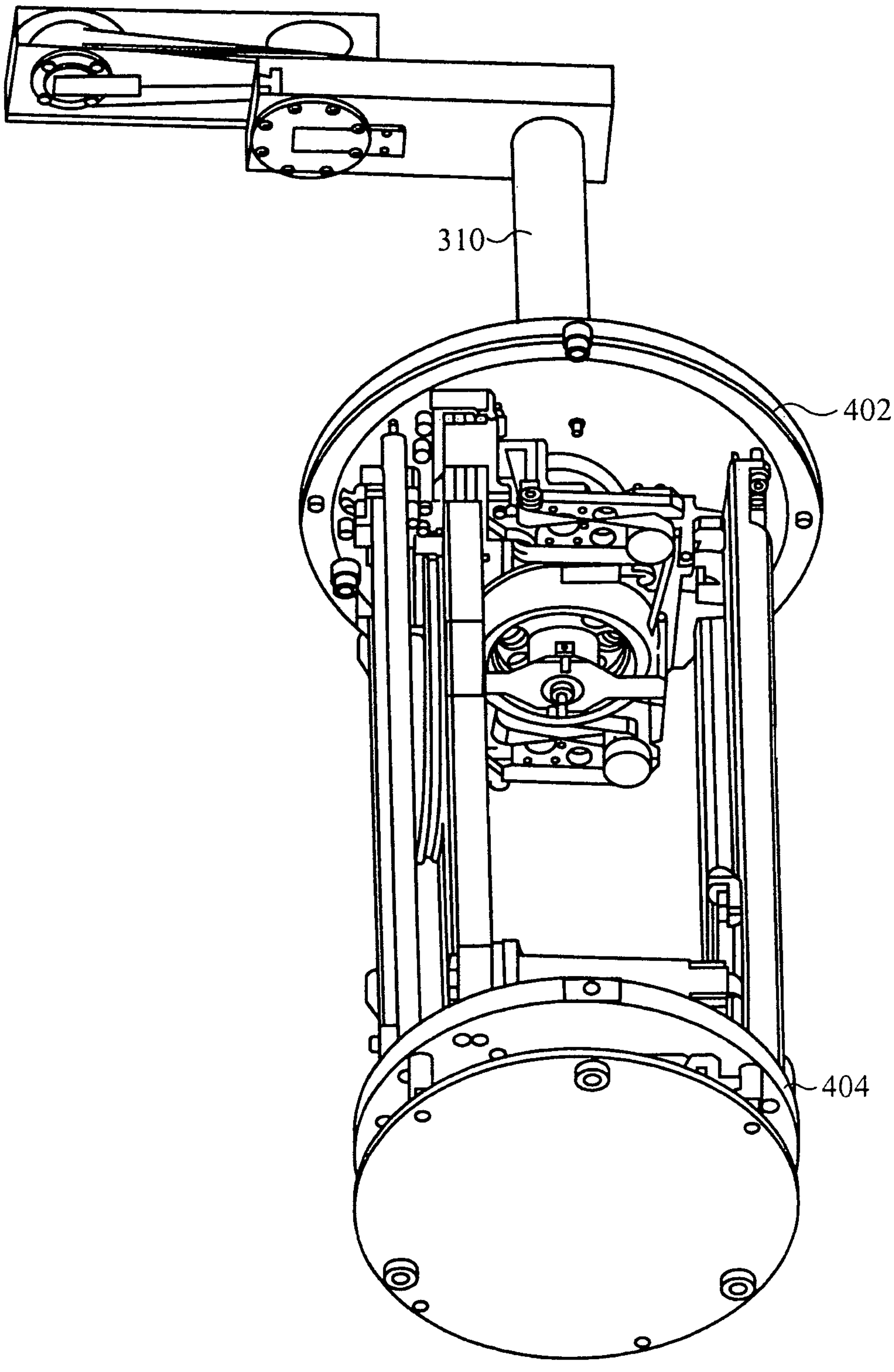


Fig. 7

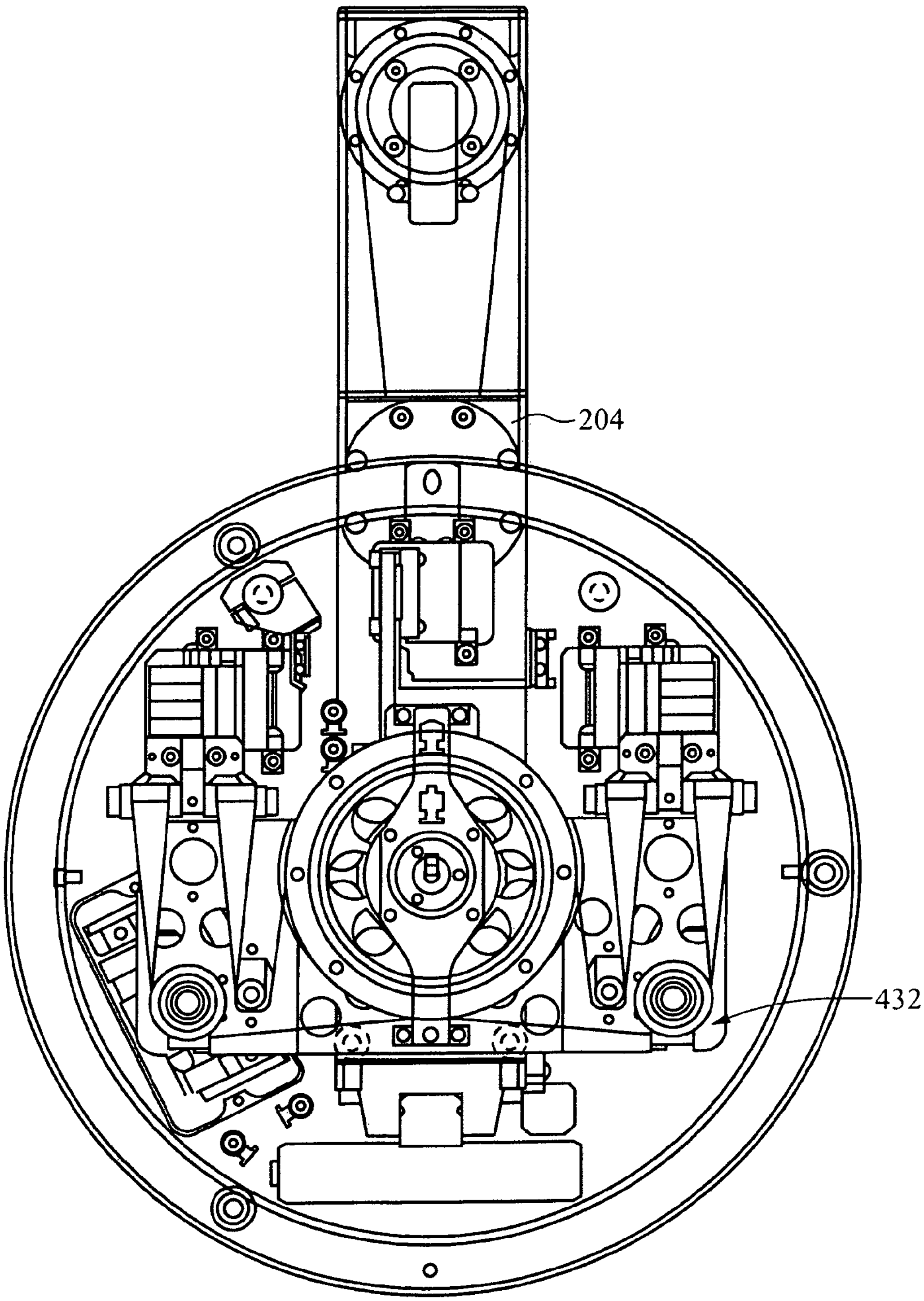


Fig. 8

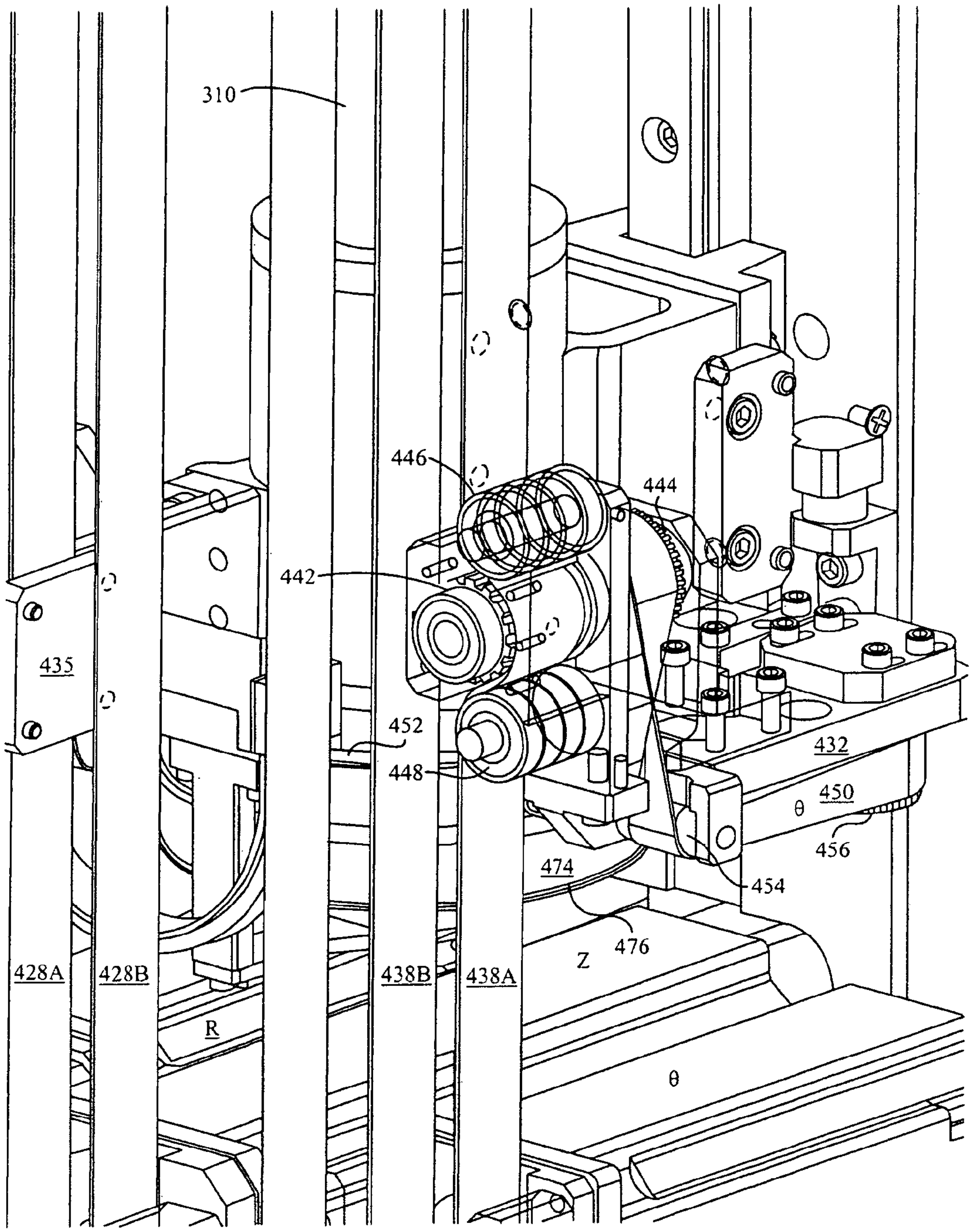

310
446
444
442
435
452
448
432
450
θ
456
454
474
476
Z
428A
428B
438B
438A
R
θ

Fig. 9A

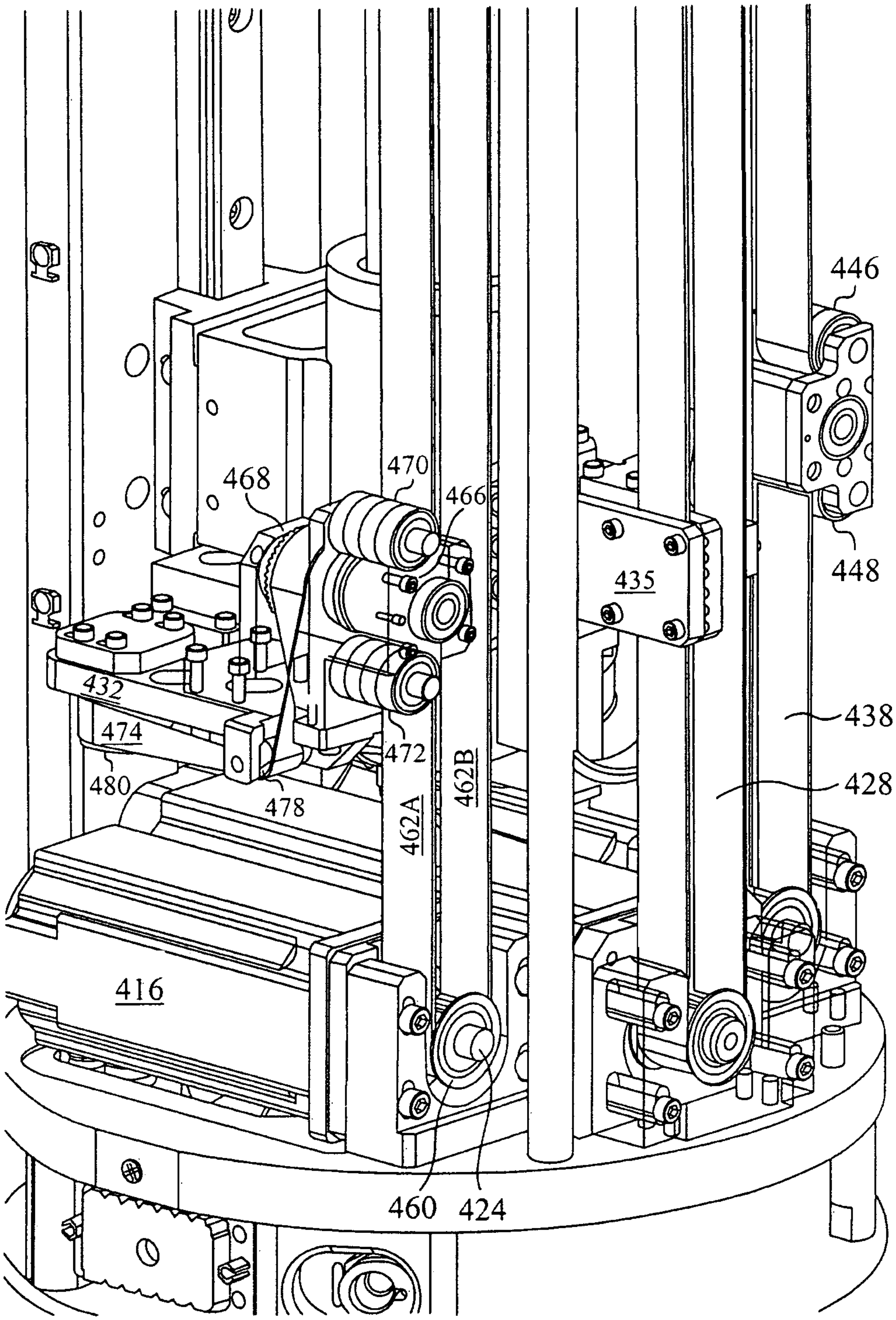

446
470
468
466
448
435
432
474
472
438
480
478
462B
462A
428
416
460
424

Fig. 9B

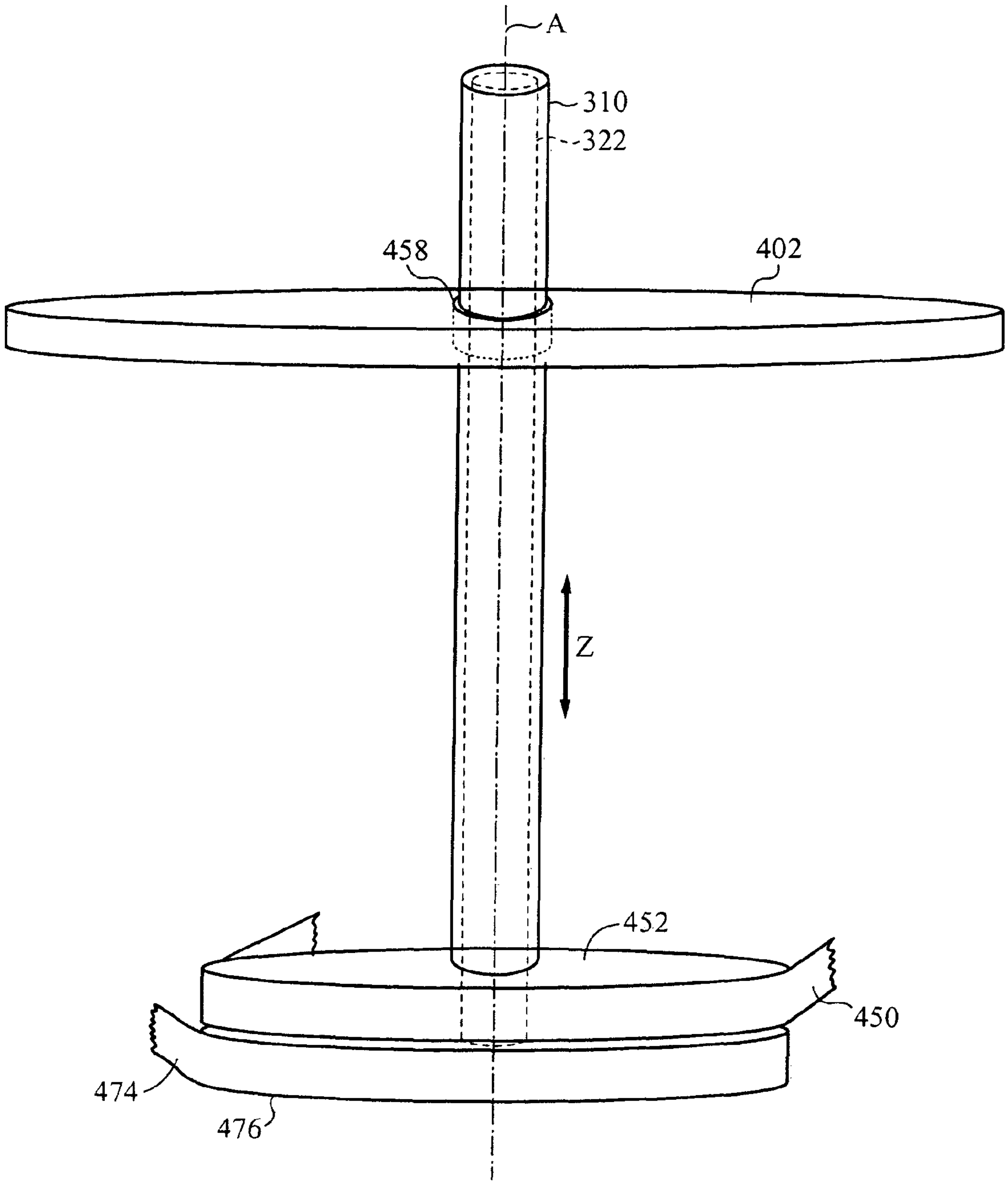


Fig. 9C

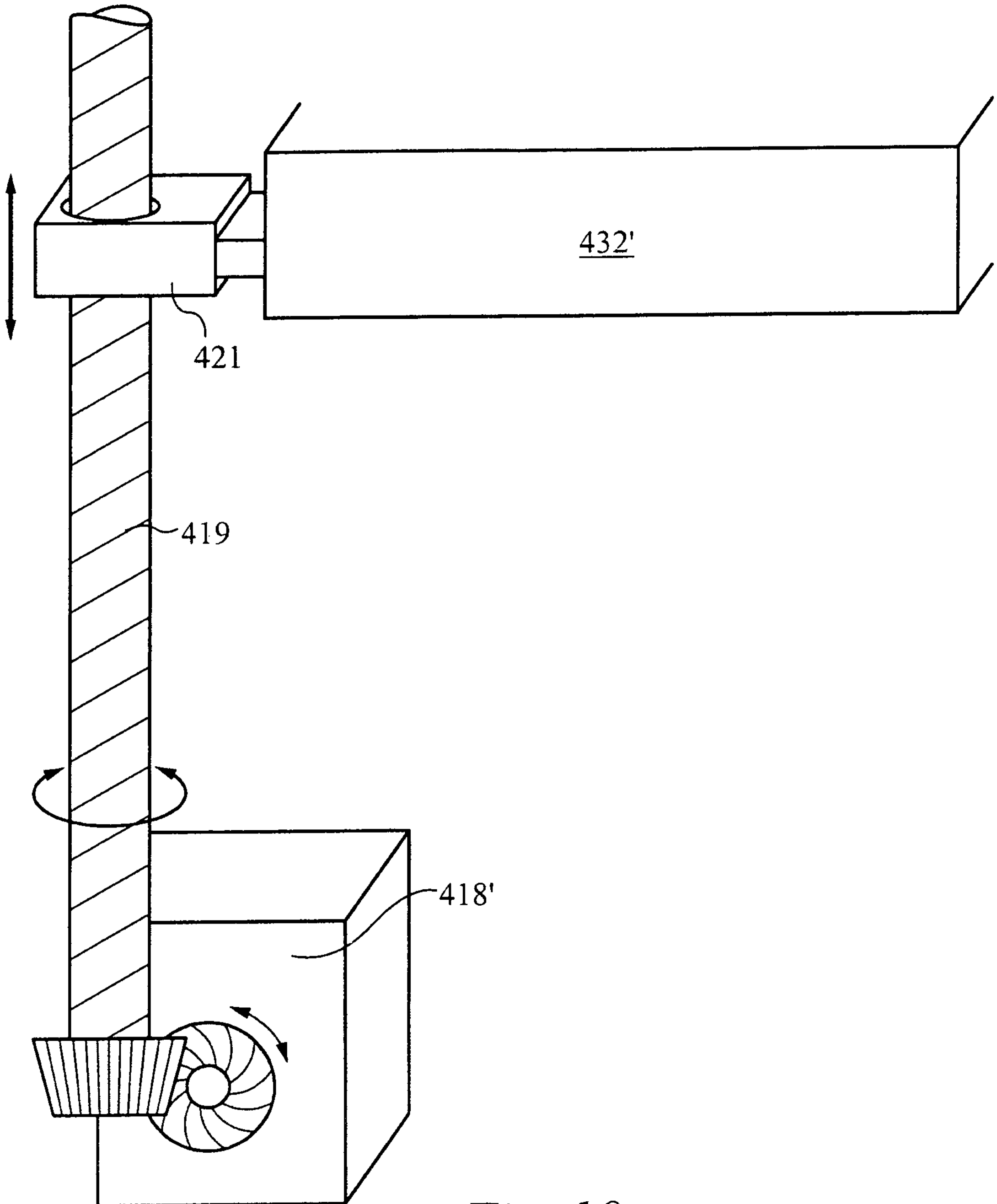


Fig. 10

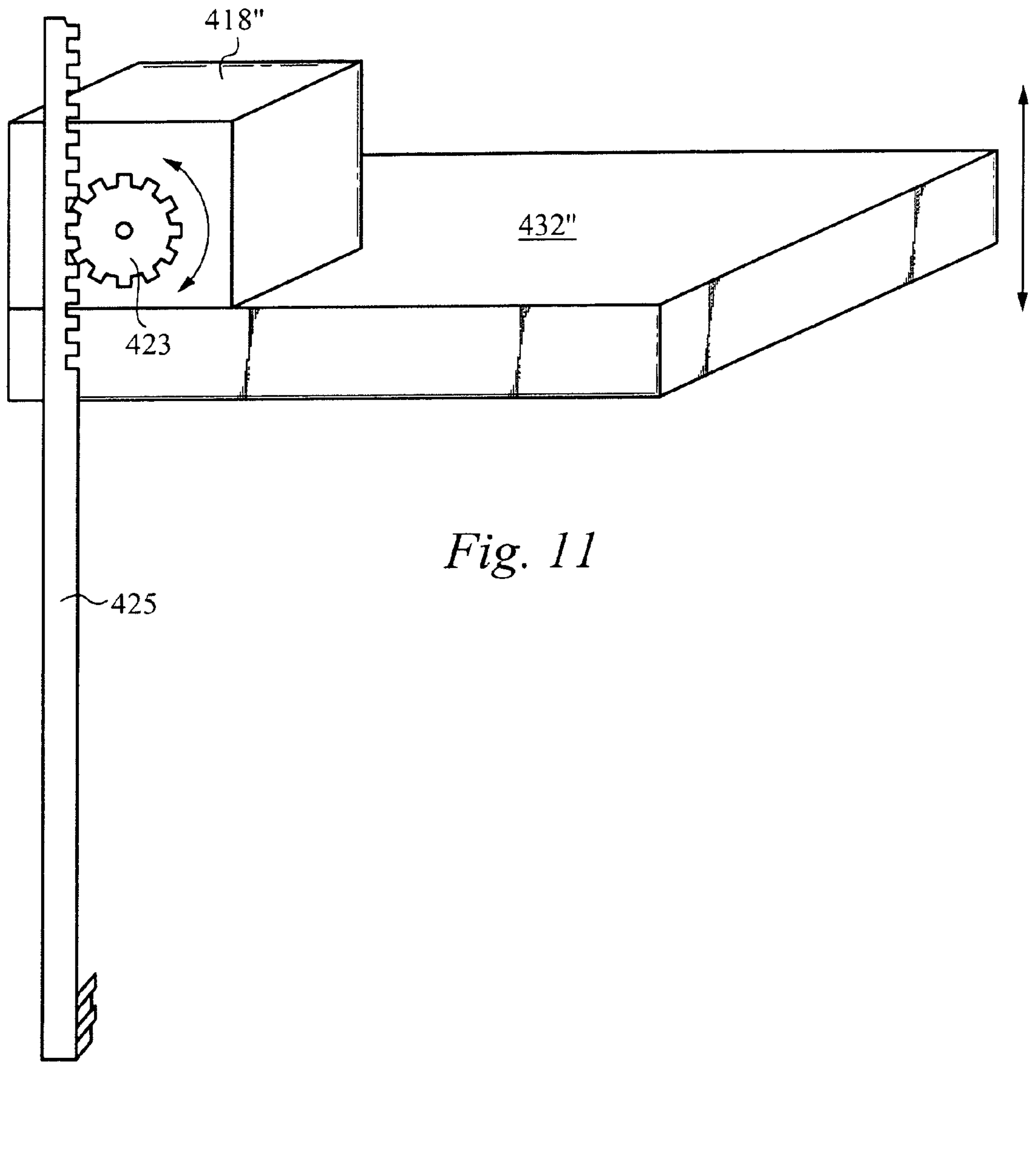


Fig. 11

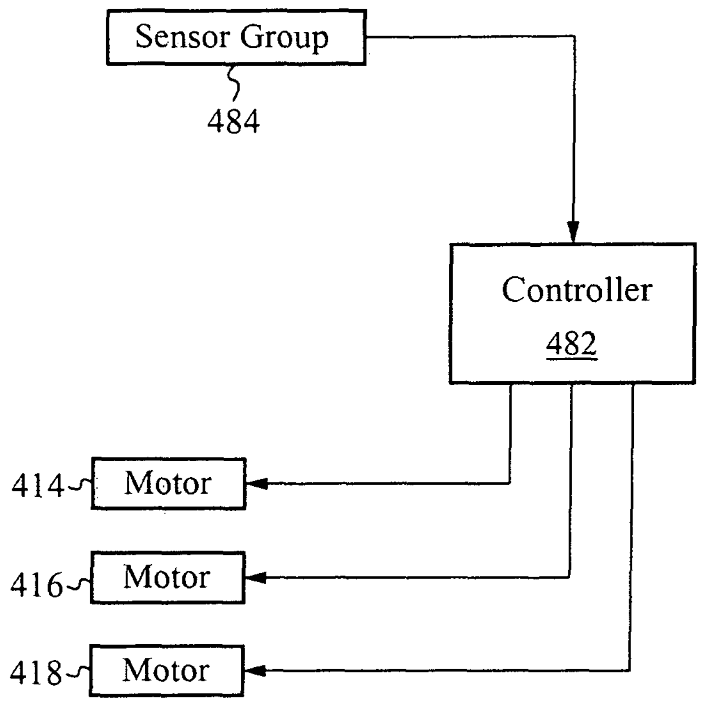

Sensor Group
484
Controller
482
414
Motor
416
Motor
418
Motor

Fig. 12

ROBOT WITH BELT-DRIVE SYSTEM

RELATED APPLICATIONS

This application is the parent application for child application Ser. No. 11/520,982, now U.S. Pat. No. 8,220,354 B2, which was filed as a continuation-in-part of the instant application.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The invention relates to robots used for substrate transport in semiconductor processing.

2. Description of the Related Art

Robots are commonly used in semiconductor processing environments, in order to transport substrates such as wafers to and from storage locations or various processing stations. The highly repetitive nature of the motions involved and the speeds required for high throughput make robots ideal candidates for these tasks. The types of motions of which these types of robots are capable vary. Typically, a robot having a robot body and robot arm extending from the robot body will exhibit angular (θ), radial (R) and Z motions in a cylindrical coordinate system. Angular motion refers to rotation of the robot arm about a primary axis at which it is pivotably coupled to the robot body. Radial motion is extension/retraction motion of the robot arm to and from the primary axis. Z motion is elevation of the robot arm (up-down) with respect to the robot body. Details of operation of such robots are described in U.S. Pat. No. 5,789,890, entitled "ROBOT HAVING MULTIPLE DEGREES OF FREEDOM (Genov et al.), incorporated herein by reference in its entirety.

Issues that are of concern in these types of robots include weight, size, complexity, and range. The present invention seeks to address one or more of these issues, to thereby improve factors such as robot performance, reliability, and throughput, and to increase longevity and reduce costs of robot manufacture and maintenance.

BRIEF SUMMARY OF THE INVENTION

In accordance with one aspect of the invention, there is provided a robot that includes a robot arm and a robot body. Also included is a floating Z platform mounted for motion in a Z direction in the robot body, a shaft coupled to the robot arm and to the floating Z platform, the shaft being rotatable about a primary axis and movable with the floating Z platform, a first motor configured to impart Z motion to the floating Z platform and to the shaft, a primary timing belt stationarily mounted in the robot body, a second motor configured to rotate the primary timing belt, and a secondary timing belt coupled to the primary timing belt and to the shaft to thereby transfer motion of the primary timing belt to the robot arm by way of said shaft.

In accordance with a further aspect of the invention, there is provided an assembly for providing a robot having a robot arm and a robot body with Z motion and at least one of R and θ motions. The assembly includes a floating platform configured for translation relative to the robot body in a first direction, a shaft coupled to the robot arm and supported by the floating platform, the shaft being translatable with the floating platform in the first direction and being axially rotatable about a primary axis extending in the first direction, a first motor mounted stationarily relative to the robot body such that translation of the floating platform and shaft occurs relative to the first motor, a second motor mounted stationarily relative to the body such that translation of the floating platform and shaft occurs relative to the second motor, a first linkage coupling the first motor to the floating platform such that the first motor is capable of motivating the translation of the floating platform and the shaft, and a second linkage coupling the second motor to the shaft such that the second motor is capable of motivating the axial rotation of the shaft. The second linkage includes a primary timing belt stationarily mounted relative to the robot body, and a motion conversion assembly translatable with the floating platform and the shaft, the motion conversion assembly including a secondary timing belt coupled to the primary timing belt.

In accordance with a further aspect of the invention, there is provided a method for enabling a robot having a robot arm and a robot body to undergo Z motion and at least one of radial (R) and angular (θ) motions. The method includes coupling motion of a first motor that is stationarily mounted with respect to the robot body to the robot arm by way of a shaft that is mounted for axial translation along a primary axis in response to the first motor motion, and coupling motion of a second motor that is stationarily mounted with respect to the robot body to the robot arm by way of the shaft, the shaft being mounted for rotation about the primary axis in response to the second motor motion. The coupling of motion of a second motor includes, in response to rotation of the second motor, rotating a primary timing belt that is stationarily mounted with respect to the robot body, and converting the rotation of the primary timing belt to the rotation of the shaft about the primary axis using a motion conversion assembly that is configured to translate axially with the shaft.

In accordance with a further aspect of the invention, there is provided an apparatus for enabling a robot having a robot arm and a robot body to undergo Z motion and at least one of radial (R) and angular (θ) motions. The apparatus includes means for coupling motion of a first motor that is stationarily mounted with respect to the robot body to the robot arm by way of a shaft that is mounted for axial translation along a primary axis in response to said the motor motion, and means for coupling motion of a second motor that is stationarily mounted with respect to the robot body to the robot arm by way of the shaft, the shaft being mounted for rotation about the primary axis in response to the second motor motion. The means for coupling motion of a second motor is operative to, in response to rotation of the second motor, rotate a primary timing belt that is stationarily mounted with respect to the robot body, and convert the rotation of the primary timing belt to the rotation of the shaft about the primary axis using a motion conversion assembly that is configured to translate axially with the shaft.

In accordance with a further aspect of the invention, there is provided a method for providing motion to a robot arm in a robot having a Z motion linkage capable of imparting Z motion to a robot arm, a robot body angular (θ) motion linkage capable of imparting angular motion to the robot arm, and a robot body radial (R) motion linkage capable of imparting radial motion to the robot arm. The method includes actuating a first motor coupled to the robot arm by way of the Z motion linkage, actuating a second motor coupled to the robot arm by way of the robot body angular (θ) motion linkage, actuating a third motor coupled to the robot arm by way of the robot body radial (R) motion linkage, and synchronizing the first, second and third motors such that the robot arm undergoes Z motion while maintaining fixed angular (θ) and radial (R) positions.

In accordance with a further aspect of the invention, there is provided a computer readable medium containing a program that causes a robot having a Z motion linkage capable of imparting Z motion to a robot arm, a robot body angular (θ) motion linkage capable of imparting angular motion to the robot arm, and a robot body radial (R) motion linkage capable of imparting radial motion to the robot arm, to undergo motion based on a procedure that includes actuation of a first motor coupled to the robot arm by way of the Z motion linkage, actuation of a second motor coupled to the robot arm by way of the robot body angular (θ) motion linkage, actuation of a third motor coupled to the robot arm by way of the robot body radial (R) motion linkage, and synchronization of the first, second and third motors such that the robot arm undergoes Z motion while maintaining fixed angular (θ) and radial (R) positions.

Advantages provided by some or all of the invention aspects disclosed herein include light weight due to the types and arrangement of linkages and components. This minimizes robot weight and reduces component inertia, thereby allowing for greater operational speeds, and reduced wear. Another advantage is the ability to achieve angular rotation of the robot arm that is "endless"—that is, greater than 360 degrees, without the hinderance of cables or the like that would twist and limit rotation. Other advantages will become evident from a reading of the description below.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

Many advantages of the present invention will be apparent to those skilled in the art with a reading of this specification in conjunction with the attached drawings, wherein like reference numerals are applied to like elements, and wherein:

FIG. **1** is a top plan view of a semiconductor processing environment including a robot;

FIG. **2** is a schematic view of the robot of FIG. **1**

FIG. **3** is a schematic view detailing the motions of the robot arm of the robot of FIG. **2**;

FIGS. **4**-**9**B are perspective views showing details of the interior of the robot of FIG. **2**;

FIG. **9**C is a schematic view showing the connection of the coaxial shafts to the respective large pulleys driven by the secondary timing belts;

FIG. **10** is a schematic view of an alternative Z motion linkage using a threaded rod and engaged threaded nut;

FIG. **11** is a schematic view of an alternative Z motion linkage using a rack and pinion arrangement; and

FIG. **12** is a block diagram showing the controller and related components for controlling the robot of FIG. **2**.

DETAILED DESCRIPTION OF THE INVENTION

Embodiments of the present invention are described herein in the context of robots used for substrate transport in semiconductor processing. Those of ordinary skill in the art will realize that the following detailed description of the present invention is illustrative only and is not intended to be in any way limiting. Other embodiments of the present invention will readily suggest themselves to such skilled persons having the benefit of this disclosure. Reference will now be made in detail to implementations of the present invention as illustrated in the accompanying drawings. The same reference indicators will be used throughout the drawings and the following detailed description to refer to the same or like parts.

In the interest of clarity, not all of the routine features of the implementations described herein are shown and described. It will, of course, be appreciated that in the development of any such actual implementation, numerous implementation-specific decisions must be made in order to achieve the developer's specific goals, such as compliance with application- and business-related constraints, and that these specific goals will vary from one implementation to another and from one developer to another. Moreover, it will be appreciated that such a development effort might be complex and time-consuming, but would nevertheless be a routine undertaking of engineering for those of ordinary skill in the art having the benefit of this disclosure.

FIG. **1** is a top plan view of a semiconductor processing environment **100**, typically exhibiting clean room conditions. A robot **200** having a robot body **201** and a robot arm **202** is disposed between two rows of stations **106**. The robot arm **202** is configured to carry a semiconductor wafer **108**, for example a standard 300 mm wafer, between the stations **106**. Other substrates may also be similarly transported, for example 200 mm wafers, flat panel displays, and so forth. The stations **106** include for example one or more storage cassettes **110** in which the substrates—that is, the 300 mm wafers in this example—are stacked. Additional stations, such as CVD (chemical vapor deposition) stations **112**, may be provided, in which various fabrication procedures take place. Also included is a prealignment station **114** at which the wafer **108** may be deposited such that its orientation can be determined and/or adjusted. Alignment may also be conducted by the robot arm itself if suitably equipped.

FIG. **2** is a more detailed view of robot **200** of FIG. **1**. Arm **202** comprises a plurality of links **204**, **206** and **208**, the distalmost of which, **208**, engages the substrate to be transported and is herein referred to as the end effector. Robot **200** exhibits R, θ and Z motion as defined in a polar coordinate system, with the R motion being generally radial motion of the distalmost link (that is, end effector **208**) from primary axis A of the robot **200**. θ motion is rotation of arm **202** about the primary axis A. Z motion is motion of arm **202** along primary axis A (that is, "up-down" motion). In addition, end effector **208** may exhibit yaw (Y) motion, which is defined as rotation about an end effector or yaw axis B which is substantially parallel to primary axis A. While not detailed herein, additional motions, such roll and pitch of the end effector **208**, and tilting of the robot **200** relative to the Z axis, are also contemplated.

FIG. **3** is a schematic diagram illustrating details of the manner in which R and θ motions of robot arm **202** are effected. Links **204**, **206** and **208** (end effector) are pivotably coupled to one another. Taking primary axis A as the point of reference, a first, outer driving shaft **310** (i.e. first shaft) is rigidly connected to the proximalmost portion of proximalmost link **204**. Driving shaft **310** is centered about primary axis A and is mounted for rotation axially around said axis. Rotation of outer driving shaft **310** provides angular rotation—that is, the θ motion—of link **204** and robot arm **202**. Rotation takes place bidirectionally—that is, clockwise and counter-clockwise—and is, "endless", meaning that it is not limited to a full circle but can take the form of multiple, or an "infinite" number of revolutions.

An arm radial (R) motion linkage is provided to effect radial (R) motion of the robot arm **202**. The arm radial motion linkage includes a plurality of belts and pulleys coupled to the links **204**-**208**. Motion of the plurality of belts and pulleys, including belts **312** and **314** and pulleys **316**, **318** and **320**, is motivated by inner driving shaft **322** (i.e. second shaft) and is coordinated such that rotation of the inner driving shaft causes retraction or extension of arm **202** in radial (R) direction. Details of radial (R) motion implementation are provided in the aforementioned U.S. Pat. No. 5,789,890.

During maneuvering of the robot arm **202**, the θ and R motions are synchronized in a controlled manner for opti-

mum performance. Synchronization takes place by controlling the rotational motions of outer driving shaft **310** and inner driving shaft **322**, which can be moved independently of one another. Control and synchronization of arm **202** are effected in the spatial, velocity and acceleration and planes such that multi-segment smooth trajectories including non-radial straight line motion of the end effector **308** can be achieved. The term "non-radial" is with reference to primary axis A and means that the end effector **208** is movable in a straight line that does not pass through said primary axis. During this and other motions, the orientation of the end effector **208** can be preserved or controllably altered as desired. One manner of providing this feature is through the use of independent yaw motion of the end effector **208**. It will be appreciated that the arrangement described herein is exemplary only and that other arrangements for effecting θ, R and Y motions are contemplated, including those that use different numbers of pulleys and belts, different gearing ratios, and so forth. It will also be appreciated that while the discussion herein is directed to robot arms having three links, the same principles are applicable to greater or lesser number of links and the
concepts described herein are equally applicable to such devices. Further details of the manner in which θ, R and Y motions are achieved and synchronized in a robot arm such as arm **202** can be found for example in the aforementioned U.S. Pat. No. 5,789,890.

FIGS. **4**-**9**B are various views showing inner details of robot body **201**. A portion of arm **202** excluding end effector **208** is also shown, in a first elevation in FIG. **4** and in a higher elevation in FIG. **5**. Inner (**322**) and outer driving (**310**) shafts are shown in their lowest position in FIG. **4**. They are also shown in a raised position in FIG. **5**, such that robot arm **202** is at its lowest height or Z position in FIG. **4**, and is at a higher elevation or Z position in FIG. **5**.

As seen from the drawings, a frame structure is comprised of a top plate **402** and base plate **404**. These are mounted substantially parallel to one another and supported by a side plate **406** and a pair of vertical supports **408** and **410**. Base plate **404** may be raised above a bottom flange **412**, with sufficient clearance to accommodate circuit boards or other components (not shown) if desired.

Disposed between top plate **402** and base plate **404** are three motors, **414**, **416** and **418** dedicated respectively to the θ, R and Z motions exhibited by the robot **200**. The motors are mounted horizontally—that is, each of their drive shafts lies substantially in a horizontal plane which is parallel to base plate **404** on which the motors are preferably mounted, and is disposed substantially perpendicularly to the primary axis A about which the inner (**322**) and outer (**310**) driving shafts are disposed. A robot body angular (θ) motion linkage, of which outer driving shaft **310** is part, transfers rotational motion of drive shaft **420** of motor **414** to proximalmost link **204** of robot arm **202** such that angular (θ) motion of the robot arm is achieved. A robot body radial (R) motion linkage, of which inner driving shaft **322** is part, transfers rotational motion of drive shaft **422** of motor **416** to the arm radial motion linkage such that radial (R) motion of robot arm **202** is achieved. A Z motion linkage transfers rotational motion of drive shaft **424** of motor **418** to axial motion of inner (**322**) and outer (**310**) driving shafts such that Z motion of arm **202** attached thereto is achieved.

The Z motion linkage includes a first drive pulley **426** coupled for rotation with drive shaft **424** of motor **418**. Either direct drive or a geared drive of pulley **426** by drive shaft **424** is contemplated. Drive pulley **426** is geared, or toothed, and engages with and rotates timing belt **428** which extends between drive pulley **426** and driven idler pulley (also toothed or geared) **430** mounted to the bottom-facing portion of top plate **402**. Timing belt **428** is thus stationarily mounted in robot body **201**, meaning that even though it rotates, its position in the robot body does not change. Timing belt **428** (i.e. additional belt) is provided with teeth on the interior face thereof, said teeth engaging the teeth of drive pulley **426** and the teeth of driven idler pulley **430** to minimize relative slippage between the timing belt and the pulleys. As an alternative to a belt, which is preferably made of Kevlar™ or other minimal stretch material, a stainless steel band having suitable slots or holes for engaging appropriately-configured teeth on drive pulley **426** and idler pulley **430** can be used. Timing belt **428** is kept in tension to minimize slack. To provide adjustment of this tension, vertical adjustment of the position of drive pulley **426** and/or of idler pulley **430** can be provided, using a suitable adjustment mechanism, such as set screws (not shown) or the like. Moving one or both the drive pulley **426** and/or of idler pulley **430** pulleys apart increases the tension of belt **428**, and moving them closer together reduces tension. In the preferred direct drive case, moving drive pulley **426** may entail moving the motor **418** and shaft **424** on which the drive pulley is mounted. This can be accomplished in a simple manner using set screws (not shown) or the like for instance.

A floating Z platform **432** supporting coaxial or nested driving shafts **310** and **322** is provided. Floating Z platform **432** is movable vertically (up-down) and is guided in said motion by a linear guide **434** provided on support plate **406**. The guide serves to limit motion of floating Z platform **432** to a single direction—the Z direction. Motion of Z platform **432** is tied to that of timing belt **428**. This is accomplished by providing a clamp **435** or similar connection mechanism which is rigidly attached to Z platform **432** and which is clamped to timing belt **428** such that it is immovable relative to the belt. It will be appreciated that clamp **435** should be clamped to a portion of timing belt **428** that exhibits Z (up-down) motion, but that the configuration of the timing belt can be different from that shown. In other words, timing belt **428** can have more than the two legs (**428***a*, **428***b*) shown (FIG. **9**A), and these legs do not all have to extend vertically or even be in the same plane, so long as at least a portion of one leg extends vertically, to which portion the clamp **435** should be coupled. When motor **418** is actuated, it rotates drive pulley **426**, which moves timing belt **428**, thereby vertically moving Z platform **432** clamped thereto. This causes shafts **310** and **322** to move vertically, and, commensurately, arm **202** coupled to the upper portions of the shafts. Because the motors **414**, **416** and **418** are disposed at the bottom of the interior region of robot body **201** and are preferably side by side and arranged such that they are parallel to and close to the base plate **404**, they provide clearance for Z platform **432**, allowing its descent unimpeded towards the bottom of the robot body **201**. This allows for a vertically more compact robot body and/or more Z travel for robot arm **202**.

It will be appreciated that in other embodiments the Z motion linkage can be a means for motivating the Z platform in the Z direction other than timing belt **432** and clamp **435**. Instead, a screw-type mechanism can be used, as shown in FIG. **10**, in which a motor **418'** rotates a vertically mounted threaded rod **419** which engages threaded nut **421** rigidly mounted to the floating Z platform **432'**. Alternatively, a rack-and-pinion arrangement as shown in FIG. **11** can be used, wherein a motor **418"** mounted in floating Z platform **432"** rotates a pinion **423** which engages a toothed rack **425**, imparting Z motion to the floating Z platform on which the motor and pinion are mounted.

The robot body angular (θ) motion linkage includes a first drive pulley **436** coupled for rotation with drive shaft **420** of motor **414**. Again, either direct drive or a geared drive is contemplated. Drive pulley **436** is geared, or toothed, and serves to rotate a primary timing belt **438** which extends between drive pulley **436** and driven idler pulley (also toothed or geared) **440** mounted to the bottom-facing portion of top plate **402**. Primary timing belt **438** is thus stationarily mounted in robot body **201**, meaning that even though it rotates, its position in the robot body does not change. Primary timing belt **438** is provided with teeth on the interior face thereof, these teeth engaging the teeth of drive pulley **436** and driven idler pulley **440** to minimize relative slippage of the timing belt and pulleys. As an alternative to a belt, which is preferably made of Kevlar™ or other minimal-stretch material, a stainless steel band having suitable slots or holes for engaging appropriately-configured teeth on drive pulley **436** and idler pulley **440** can be used. Primary timing belt **438** is kept in tension to minimize slack. To provide adjustment of this tension, the position of drive pulley **436** and/or of idler pulley **440** can be adjusted vertically. Moving one or both of these pulleys apart increases the tension of belt **438**, and moving them towards one another reduces the tension. Of course, in the preferred direct drive case, moving drive pulley **436** entails moving the motor **414** and shaft **420** on which the drive pulley is mounted. This can be accomplished in a simple manner using set screws (not shown) for instance.

An angular (θ) motion conversion assembly is mounted to floating Z platform **432** and coupled to primary timing belt **438**. The angular (θ) motion conversion assembly includes a driving (**442**) and a driven (**444**) pulley (FIG. **9**A) that are axially coupled to one another such that rotation of driving pulley **442** causes rotation of driven pulley **444**. The pulleys **442** and **444** are toothed, with the teeth of driving pulley **442** engaging the teeth of primary timing belt **438**. Guiding wheels **446** and **448** provided on either side of driving pulley **442** serve to bias the driving pulley against primary timing belt **438** for proper engagement therewith. The teeth of driven pulley **444** engage the teeth of a secondary timing belt **450** which is coupled to outer driving shaft **310** by way of a large, toothed pulley **452** mounted axially to the base of the driving shaft (FIG. **9**C). As an alternative to a belt, which is preferably made of Kevlar™ or other minimal stretch material, a stainless steel band having suitable slots or holes for engaging appropriately-configured teeth on driven pulley **444** and large pulley **452** can be used. Secondary timing belt **450** has a 90-degree "folded" configuration such that rotation of pulleys **442** and **444** in a first (horizontal) axis is converted to rotation of outer driving shaft **310** in a second (vertical) axis. Folding is effected using an arrangement of freely rotating pins or wheels **454**, optionally in combination with toothed pulleys **456**, around which the secondary timing belt **450** is directed to achieve the desired directional changes. Large pulley **452** is rotationally mounted in floating Z platform **432** and is rigidly connected to the base of outer driving shaft **310** such that its rotational motion is caused by secondary timing belt **450**. (See FIG. **9**C). Shaft **310** (and shaft **322**) passes through top plate **402** and is free to rotate and slide axially (up-down) therein. A bearing **458** in top plate **402** facilitates this. Axial (up-down) motion of outer shaft **310** is coupled to axial motion of inner shaft **322** disposed therein such that the two shafts move axially (Z motion) together along the robot primary axis. However, rotational motion of the two shafts is independent—that is, the two shafts may simultaneously or alternately rotate in the same direction at the same or different rates, or they may rotate in opposite directions at the same or different rates. Suitable bearings (not shown) are provided to ensure this. The two shafts **310** and **322** are therefore rotationally independent of one another. It will be appreciated that driving pulley **442** of the angular (θ) motion conversion assembly should couple to a portion of primary timing belt **438** that extends in the Z (up-down) direction commensurately with the travel of the floating Z platform **432** to which the angular (θ) motion conversion assembly is mounted, but that the configuration of the primary timing belt can be different from that shown. In other words, the primary timing belt **438** can have more than the two legs (**438***a*, **438***b*) shown (FIG. **9**A), and these legs do not all have to extend vertically or even be in the same plane, so long as at least a portion of one leg extends vertically to the same extent as the travel of the floating Z platform **432**.

The robot body radial (R) motion linkage includes a first drive pulley **460** coupled for rotation with drive shaft **422** of motor **416**. Again, either direct drive or a geared drive is contemplated. Drive pulley **460** is geared, or toothed, and serves to rotate a primary timing belt **462** which extends between drive pulley **460** and driven idler pulley (also toothed or geared) **464** mounted to the bottom-facing portion of top plate **402**. Primary timing belt **462** is thus stationarily mounted in robot body **201**, meaning that even though it rotates, its position in the robot body does not change. Primary timing belt **462** is provided with teeth on the interior face thereof, these teeth engaging the teeth of drive pulley **460** and driven idler pulley **464** to minimize relative slippage of the timing belt and pulleys. As an alternative to a belt, which is preferably made of Kevlar™ or other minimal-stretch material, a stainless steel band having suitable slots or holes for engaging appropriately-configured teeth on drive pulley **460** and idler pulley **464** can be used. Primary timing belt **462** is kept in tension to minimize slack. To provide adjustment of this tension, the position of drive pulley **460** and/or of idler pulley **464** can be adjusted vertically. Moving one or both of these pulleys apart increases the tension of belt **462**, and moving them towards one another reduces the tension. Of course, in the preferred direct drive case, moving drive pulley **460** entails moving the motor **416** and shaft **422** on which the drive pulley is mounted. This can be accomplished in a simple manner using set screws (not shown) for instance.

A radial (R) motion conversion assembly (i.e. additional motion conversion assembly) is mounted to floating Z platform **432** and coupled to primary timing belt **462** (i.e. additional timing belt), as detailed in FIG. **9**B. The radial (R) motion conversion assembly includes a driving (**466**) and a driven (**468**) pulley (i.e. additional driving pulley and driven pulley) that are axially coupled to one another such that rotation of driving pulley **466** causes rotation of driven pulley **468**. The pulleys **466** and **468** are toothed, with the teeth of driving pulley **466** engaging the teeth of primary timing belt **462**. Guiding wheels **470** and **472** provided on either side of driving pulley **466** serve to bias the driving pulley against primary timing belt **462** for proper engagement therewith. The teeth of driven pulley **468** engage the teeth of a secondary timing belt **474** (i.e. additional secondary timing belt) which is coupled to inner driving shaft **322** by way of a large, toothed pulley **476** attached axially to the base of the driving shaft (FIG. **9**C). As an alternative to a belt, which is preferably made of KEVLAR™ or other minimal stretch material, a stainless steel band having suitable slots or holes for engaging appropriately-configured teeth on driven pulley **468** and large pulley **476** can be used. Secondary timing belt **474** has a 90-degree "folded" configuration such that rotation of pulleys **466** and **468** in a first (horizontal) axis is converted to rotation of inner driving shaft **322** in a second (vertical) axis. Folding is effected using an arrangement of freely rotating pins or wheels **478**, optionally in combination with toothed pulleys **480**, around which the secondary timing belt **474** is directed to achieve the desired directional changes. Large pulley **476** is rotationally mounted in floating Z platform **432** below and coaxially with large toothed pulley **452** and is rigidly connected to the base of inner driving shaft **322** such that its rotational motion caused by secondary timing belt **474** is transferred to rotation of the inner shaft. Inner shaft **322** is nested in outer shaft **310**, both of which pass through top plate **402** and are free to rotate and slide axially (up-down) therein. A bearing **458** in top plate **402** between the plate and outer driving shaft **310** facilitates this, along with a bearing between the shaft to facilitate their rotation independently of one another. As stated above, independent rotational motion of the shafts means that the two shafts may simultaneously or alternately rotate in the same direction at the same or different rates, or they may rotate in opposite directions at the same or different rates. It will be appreciated that driving pulley **466** of the radial (R) motion conversion assembly should couple to a portion (**462***a*, **462***b*) of primary timing belt **462** that extends in the Z (up-down) direction commensurately with the travel of the floating Z platform **432** to which the radial (R) motion conversion assembly is mounted, but that the configuration of the primary timing belt **462** can be different from that shown. In other words, the primary timing belt **462** can have more than the two legs **462***a*, **462***b* shown, and these legs do not all have to extend vertically or even be in the same plane, so long as at least a portion of one leg extends vertically to the same extent as the travel of the floating Z platform **432**.

The arrangement detailed above provides the robot **200** with motion along three axes—R, θ and Z. That is, robot **200** is thus provided with three degrees of freedom. Moreover, angular (θ) motion is unrestricted, meaning that an "endless" number of revolutions of robot arm **202** is possible, with no cables or other mechanical encumbrances preventing rotations of greater than 360 degrees. In addition, other degrees of freedom, including yaw (Y), pitch and roll of the end effector **208** are possible, in accordance with principles described in the aforementioned U.S. Pat. No. 5,789,890, entitled "ROBOT HAVING MULTIPLE DEGREES OF FREEDOM (Genov et al.)

It will be appreciated that because of the manner in which the robot body angular (θ) motion linkage and the robot body radial (R) motion linkage are coupled to the Z motion linkage, Z motion must be synchronized with angular (θ) and radial (R) motions. For instance, consider the case in which only Z motion is desired, and the angular (θ) and radial (R) positions of the robot arm **202** are to remain unchanged—that is, no angular (θ) or radial (R) motions are to occur. As floating Z platform **432** is raised or lowered by action of motor **418** and timing belt **428**, motors **414** and **416** must also be actuated so that no relative motion between primary timing belt **438** and driving pulley **442** of the angular (θ) motion conversion assembly takes place, and also so that no relative motion between primary timing belt **462** and driving pulley **466** of the radial (R) motion conversion assembly takes place, because such relative motions would cause angular (θ) or radial (R) displacement of robot arm **202**. In the case of the floating Z platform **432** being raised, motors **414** and **416** would need to be actuated in a first direction, and in the case of floating Z platform **432** being lowered, motors **414** and **416** would need to be actuated in a second, opposite direction. Consider also the case in which only angular (θ) motion is desired. This would require activation of motor **414** only. Similarly, if only radial (R) motion is desired, only motor **416** need be activated.

It will be noted that in practice, during translation of floating Z platform **432** in the Z direction, relative motion between primary timing belt **438** and driving pulley **442** of the angular (θ) motion conversion assembly, along with relative motion between primary timing belt **462** and driving pulley **466** of the radial (R) motion conversion assembly, may in fact be desired, so that motion of the robot arm **202** can take place in multiple degrees of freedom simultaneously, in order shorten or optimize trajectories and travel times and thereby increase robot speed and performance. The relative motions can take place at different rates and in opposite directions depending on the desired trajectory, and actuation of motors **414**, **416** and **418** can be controlled accordingly. Of course all motor actuation is provided by a controller which is programmable such that it causes actuation of the motors in any fashion necessary to achieve the desired trajectories of robot arm **202**. This is illustrated in FIG. **12**, which shows that the controller **482** provides actuation signals to the motors **414**, **416**, and **418**. The controller operates at least in part based on sensor signals from sensor group **484**. The sensor signals derive from one or more sensors (not shown) which determine for example the positions of various robot components using devices such as encoders and so forth. In this manner controller **482** is provided with feedback according to which it issues the actuation signals to the motors. The controller **482** may be external to the robot **200** or internal thereto, or it may be partially external such that some components thereof are external, and partially internal such that other components thereof are internal.

The above are exemplary modes of carrying out the invention and are not intended to be limiting. It will be apparent to those of ordinary skill in the art that modifications thereto can be made without departure from the spirit and scope of the invention as set forth in the following claims.

The invention claimed is:

1. An assembly comprising:

a platform configured for motion in a first direction;

a first shaft extending in the first direction and supported by the platform for axial translation in the first direction;

a primary timing belt having a first portion that is movable in the first direction; and a motion conversion assembly including:

- a driving pulley rotatable by the first portion of the primary timing belt; and
- a secondary timing belt coupled to the first shaft and driven by the driving pulley such that rotation of the driving pulley caused by motion of the first portion of the primary timing belt in the first direction imparts axial rotation of the first shaft;

a second shaft extending in the first direction and supported by the platform for axial translation in the first direction;

an additional primary timing belt having a first portion that is movable in the first direction; and

an additional motion conversion assembly including:

- an additional driving pulley rotatable by the first portion of the additional primary timing belt; and
- an additional secondary timing belt coupled to the second shaft and driven by the additional driving pulley such that rotation of the additional driving pulley caused by motion of the first portion of the additional primary timing belt in the first direction imparts axial rotation of the second shaft.

2. The assembly of claim **1**, further comprising:

an additional belt having a first portion movable in the first direction, the platform being coupled to the first portion of the additional belt for motion therewith in the first direction.

3. The assembly of claim **1**, further comprising:

a robot arm coupled to the first shaft, wherein axial rotation of the first shaft imparts angular (θ) motion to the robot arm.

4. The assembly of claim **1**, further comprising:

a robot arm coupled to the first shaft, wherein axial rotation of the first shaft imparts radial (R) motion to the robot arm.

5. The assembly of claim **1**, further comprising:

a robot arm coupled to the first and second shafts, wherein axial rotation of the first shaft imparts angular (θ) motion to the robot arm, and axial rotation of the second shaft imparts radial (R) motion to the robot arm.

6. The assembly of claim **3**, wherein the robot arm includes a plurality of pivotably coupled links, the proximalmost of said links being mounted for rotation about the first direction to thereby provide said angular (θ) motion.

7. The assembly of claim **4**, wherein the robot arm includes a plurality of pivotably coupled links and an arm radial motion linkage configured to transfer rotation of said first shaft to the distalmost link to thereby provide said radial (R) motion.

8. The assembly of claim **5**, wherein the robot arm includes a plurality of pivotably coupled links, the proximalmost of said links being mounted for rotation about the first direction to thereby provide said angular (θ) motion.

9. The assembly of claim **5**, wherein the robot arm includes a plurality of pivotably coupled links and an arm radial motion linkage configured to transfer rotation of one of the first or second shafts to the distalmost link to thereby provide said radial (R) motion.

10. A robot comprising:

a platform configured for motion in a first direction;

a first shaft extending in the first direction and supported by the platform for axial translation in the first direction;

a robot arm coupled to the first shaft for motion therewith in the first direction;

a primary timing belt having a first portion that is movable in the first direction; and

a motion conversion assembly including:

a driving pulley rotatable by the first portion of the primary timing belt; and

a secondary timing belt coupled to the first shaft and driven by the driving pulley such that rotation of the driving pulley caused by motion of the first portion of the primary timing belt in the first direction imparts axial rotation of the first shaft, the axial rotation imparting to the robot arm one of angular (θ) or radial (R) motions;

a second shaft extending in the first direction and supported by the platform for axial translation in the first direction;

an additional primary timing belt having a first portion that is movable in the first direction; and

an additional motion conversion assembly including:

an additional driving pulley rotatable by the first portion of the additional primary timing belt; and

an additional secondary timing belt coupled to the second shaft and driven by the additional driving pulley such that rotation of the additional driving pulley caused by motion of the first portion of the additional primary timing belt in the first direction imparts axial rotation of the second shaft, the axial rotation imparting to the robot arm the other of the angular (θ) or radial (R) motions.

11. The robot of claim **10**, further comprising:

an additional belt having a first portion movable in the first direction, the platform being coupled to the first portion of the additional belt for motion therewith in the first direction.

12. The robot of claim **10**, wherein the robot arm includes a plurality of pivotably coupled links, the proximalmost of said links being mounted for rotation about the first direction to thereby provide said angular (θ) motion.

13. The robot of claim **10**, wherein the robot arm includes a plurality of pivotably coupled links and an arm radial motion linkage configured to transfer rotation of said first shaft to the distalmost link to thereby provide said radial (R) motion.

14. The robot of claim **10**, wherein the robot arm includes a plurality of pivotably coupled links, the proximalmost of said links being mounted for rotation about the first direction to thereby provide said angular (θ) motion.

15. The robot of claim **10**, wherein the robot arm includes a plurality of pivotably coupled links and an arm radial motion linkage configured to transfer rotation of one of said first or second shafts to the distalmost link to thereby provide said radial (R) motion.

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